Sternentstehung - Star Formation
Winter term 2017/2018
Henrik Beuther & Thomas Henning

17.10 Today: Introduction & Overview                      (H.B.)
24.10 Physical processes I                                        (H.B.)
31.10 no lecture – Reformationstag
07.11 Physical processes II                                        (H.B.)
14.11 Molecular clouds as birth places of stars            (H.L.)
21.11 Molecular clouds cont., virial & Jeans Analysis    (H.B.)
28.11 Collapse models I                                            (H.B.)
05.12 Collapse models II                                             (T.H.)
12.12 Protostellar evolution                                    (T.H.)
19.12 Pre-main sequence evolution & outflows/jets           (T.H.)
09.01 Accretion disks I                                              (T.H.)
16.01 Accretion disks II                                             (T.H.)
23.01 High-mass star formation, clusters and the IMF (H.B.)
30.01 Planet formation                                              (T.H.)
06.02 Examination week, no star formation lecture

Book: Stahler & Palla: The Formation of Stars, Wileys

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Topics today

- General concepts of massive star formation
- Outflows in high-mass star-forming regions
- Rotation and disks
- Clusters and the IMF
Massive Star Formation

- **Why important?**
  - Although few in numbers → $L \propto M^3$
  - Inject significant amounts of energy into ISM during their lifetime (outflows, radiation, supernovae).
  - Produce all the heavy elements.
  - Low-mass star formation strongly influenced by massive stars.

- Massive stars exclusively form in clusters.
- Short Kelvin-Helmholtz contraction time:

  $$t_{KH} = 3 \times 10^7 \text{ yr} \left( \frac{M_*}{1 M_\odot} \right)^2 \left( \frac{R_*}{1 R_\odot} \right)^{-1} \left( \frac{L_*}{1 L_\odot} \right)^{-1}$$

  For $60 M_\odot$, $12 R_\odot$ and $10^{5.9} L_\odot$ we find:

  $$t_{KH} \sim 11000 \text{ yr}$$

  → no observable pre-main seq. phase

- Radiation pressure important constraint.
Eddington luminosity and limit
Eddington luminosity: upper luminosity limit before star is unstable.

- **Assumptions:** spherical symmetry and fully ionized hydrogen.
  - Radiation exerts force on free electrons via Thomson scattering:
    \[
    \sigma_T = \left(\frac{q^2}{mc^2}\right)^2 \quad (\sigma_T: \text{cross sec., } q: \text{charge, } m: \text{mass})
    \]
  - Outward radial force equals rate at which electron absorbs momentum:
    \[
    \sigma_T S/c \quad (S: \text{energy flux})
    \]
  - Radiation pushes out electron-proton pairs against grav. force
    \[
    \frac{GM(m_p + m_e)}{r^2} \sim \frac{Gm_p}{r^2}
    \]
- With flux \( S = L/4\pi r^2 \), the force equilibrium is
  \[
  \frac{GMm_p}{r^2} = \sigma_T L/(4\pi r^2 c)
  \]
  \[
  \rightarrow \text{Eddington luminosity: } L_{\text{Edd}} = \frac{4\pi Gm_p c (m_p/\sigma_T)} {\kappa}
  \]
  \[
  = \frac{4\pi Gm_p c}{\kappa} \quad (\kappa = \sigma_T/m_p \text{ mass abs. coefficient})
  \]
\[
\rightarrow L_{\text{edd}} [L_{\text{sun}}] = 1.3 \times 10^{38} \left(\frac{M}{M_{\text{sun}}}\right) \text{erg/s} \sim 3 \times 10^4 \left(\frac{M}{M_{\text{sun}}}\right)
\]
- If \( L > L_{\text{edd}} \) then
  - Accretion stops if \( L \) provided by accretion
  - Gas layers pushed out and star unstable if provided by nuclear fusion.
- Scaling relations for massive (proto)stars: \( L \propto M^a \) with \( 2 < a < 4 \)
Radiation pressure

- In contrast, now the radiation pressure of the central massive (proto)star on the surrounding dust cocoon. Same relation:

\[ \frac{L}{M} = \frac{4\pi G c}{\kappa} \quad (\kappa: \text{mass abs. Coefficient}) \]

- While \( \kappa \) is very low for ionized H plasma (\( \kappa \sim 0.3 \text{cm}^2 \text{g}^{-1} \)), at the dust destruction front (T\( \sim 1500 \text{K} \)) it is considerably larger with \( \kappa \sim 10 \text{cm}^2 \text{g}^{-1} \).

\[ \Rightarrow \quad \frac{L}{M} \sim 10^3 \left[ \frac{L_{\odot}}{M_{\odot}} \right] \]

- In spherical symmetric accretion models, accretion is expected to stop as soon as the luminosity is approximately 1000 times larger than the mass of the protostar. \( \Rightarrow \) No problem for low-mass star formation.

- The critical ratio is reached for stars of approximately \( 10M_{\odot} \). Since more massive stars are known, the assumption of spherical accretion has to be wrong and other processes are needed.
Modified low-mass star formation:
- Increase accretion rates a few orders of mag.
- 2D disk geometry helps accretion processes.
- Radiation pressure can escape through outflow cavities → flashlight effect

Competetive accretion and coalescence:
- Massive stars form only in clusters.
- The cluster potential favours accretion toward objects in the cluster centers.
- All kinds of protostellar entities may merge.


Turbulent accretion: scaling up low-mass sf

- A $100M_{\text{sun}}$ star forms in $\sim 10^5$ yrs $\rightarrow$ average accretion rate $\sim 10^{-3}M_{\text{sun}}$/yr

- Standard low-mass accretion rate (Shu 1977): $\frac{dM}{dt} \sim c_s^3/G \sim 2 \times 10^{-6}M_{\text{sun}}$/yr.


$\rightarrow$ The turbulent support raises the sound speed $c_s$ and hence $\frac{dM}{dt}$.

$$\frac{dM}{dt} \sim 0.5 \times 10^{-3} \left(\frac{M_{\text{final}}}{30M_{\text{sun}}}\right)^{3/4} \Sigma_{\text{cl}}^{-3/4} \left(\frac{M}{M_{\text{final}}}\right)^{0.5} \left[\frac{M_{\text{sun}}}{\text{yr}}\right]$$

$$t \sim 1.3 \times 10^5 \left(\frac{M_{\text{final}}}{30M_{\text{sun}}}\right)^{1/4} \Sigma_{\text{cl}}^{-3/4} \left[\text{yr}\right]$$

$\Sigma_{\text{cl}}$: cloud surface density $\sim 1$ g cm$^{-2}$
Radiation pressure in 1D and 2D

Courtesy of Rolf Kuiper
Radiation pressure in 1D and 2D

Courtesy of Rolf Kuiper
Forming massive accretion disks

2D frequency-dependent hydrodynamic simulations

→ short-wavelength radiation (most effective for radiative acceleration) escapes in polar directions.

→ Radiation driven outflows in polar direction and disks in the equatorial direction are forming.

→ Massive stars may form in a similar fashion as low-mass protostars due to disk accretion.
Forming massive accretion disks

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Yorke & Sonnhalter 2002

Kuiper et al. 2010

\( M^1_{\odot} \)
3D radiative hydro simulations

- Starting with 100 to 200$M_{\text{sun}}$ cores.

- Until $\sim 17M_{\text{sun}}$ smooth accretion flow.

- Low angular momentum gas accretes directly on protostar, high angular momentum gas forms Keplerian accretion disk.

- From 17$M_{\text{sun}}$ upwards, radiation pressure starts driving out gas, bubbles form. Further infalling gas moves along the bubble walls and falls onto disk.

- Disk gravitationally instable forming more stars.

*Krumholz et al. 2009*
3D radiative hydro simulations

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Krumholz et al. 2009
Competitive Accretion

- Gas clump first fragments into large number of cores with approximately a Jeans mass. → Hence fragmentation on smaller scales.

- Each clump subsequently accretes gas from the surrounding reservoir.

- Even gas that was originally far away may finally fall onto the protostar.

Bonnell et al. 2004

Distance of gas that is ultimately accreted.

Graph showing the relationship between mass and radius for accretion.
- Required (proto)stellar densities of the order $10^6$ to $10^8$ stars per pc$^3$.

- Very explosive events expected.

- Collimated outflows and jets can barely survive.
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Single-dish maps of massive outflows

- Early observations claimed different collimation degrees for massive outflows.
  → different formation? → See high resolution image on next slide

- Outflow-mass scales with core mass.

- Outflow force implies non-radiative outflow driving.

- High outflow rates imply high accretion rates.
Collimated massive jets and outflows

IRAM 30m data
Grey: 1.2mm
Contours: CO(2-1)

Beuther et al. 2002
Collimated massive jets and outflows

Beuther et al. 2002
Outflows are ubiquitous phenomena. Jet-like outflows exist at least up to early-B and late-O-type stars. The observations suggest an evolutionary scenario.

Beuther & Shepherd 2005
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Rotation at the earliest evolutionary stages

Color: Spitzer
24 µm
Contours: SCUBA
850 µm

-12°45'00"
-12°50'00"
-12°55'00"
2.2 pc

Spitzer IRAC 3.3, 4.5 & 8 µm
Contours: PdBI 3mm

Shock-excited emission

Beuther & Steinacker 2007

Fallscheer et al. 2009

CH₃OH Velocity Moment Map

7500 AU

Contours: 1.1 mm dust continuum

kms⁻¹
ALMA observations of AFGL4176

Best fit for Keplerian disk around $25\,M_{\text{sun}}$ star

Johnston et al. 2015
- Dust lane perpendicular to outflow, diameter roughly 6000 AU.

- Model comparison with low-mass disks:
  - Quantitative parameters like mass and size exceed low-mass disks by orders of mag.
  - Qualitative parameters like density profile and disk flaring profile agree well.

*Fallscheer et al. 2011*
The disk-outflow system in Orion-source I

$\lambda 7$ mm continuum

$\lambda 7$ mm line ($SiO, v=1, 2$)

A disk?

The 1st direct evidence of an MHD disk wind?

Matthews et al. 2010
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Clusters and the Initial Mass Function (IMF)

Muench et al. 2002

Trapezium Cluster Initial Mass Function

$M_{\text{Sun}}$ 32 10 1 0.1 0.01

Log $N$ [Log $m$] + Constant

Log Mass [solar masses]

Orion Nebula

CISCO (J, K' & H2 (v=1-0 S(1))

Subaru Telescope, National Astronomical Observatory of Japan

January 28, 1999
General properties of the IMF

- Almost all stars form in clusters, isolated star formation is exception.

- Seminal paper 1955 by E. Salpeter: linear: \( \frac{dN}{dM} \sim M^{-2.35} \)  
  \( (M > M_{\text{sun}}) \) 
  \( \log: \quad \frac{d\log N}{d\log M} \sim (\log M)^{-1.35} \)

- More detailed description of the total IMF (e.g., Kroupa 2001): \( \frac{dN}{dM} \sim M^{-a} \)
  
  \( a = 0.3 \rightarrow 0.01 \leq \frac{M}{M_{\text{sun}}} \leq 0.08 \) (brown dwarf regime)

  \( a = 1.3 \rightarrow 0.08 \leq \frac{M}{M_{\text{sun}}} \leq 0.5 \)

  \( a = 2.3 \rightarrow 0.5 \leq \frac{M}{M_{\text{sun}}} \)

- Or lognormal (Chabrier 2003)

- Characteristic mass plateau around 0.5 \( M_{\text{sun}} \) (see mol. cl. lect.)

- Upper mass limit of \( \sim 150M_{\text{sun}} \)

- Largely universally valid, in clusters and the field in our Galaxy and extragalactic systems.
- Are large, massive fragments stable enough to be responsible for the Salpeter tail of the IMF, or do large clumps further fragment so that later competitive accretion may set the masses of the high-mass end?
  -- Initially, one would expect fragmentation down to the original Jeans-mass at the beginning of collapse.
  -- However, early accretion luminosity may heat the surrounding gas relatively far out → This would increase the Jeans-mass and inhibit further fragmentation.
  → Not finally solved yet!

- Mass plateau likely due to original fragmentation and thermal physics.

- At low-mass end, fragmentation may not be efficient enough and dynamical ejection could help.
Star cluster

NGC3603
6 x 6 pc
1 pc diameter
10,000 stars between 0.5 & 120 $M_{\text{sun}}$

Stolte et al. 2006
Mass segregation

NGC3603

Stolte et al. 2006
Mass segregation

Stolte et al. 2006
Summary

- Massive stars are very important for energy budget and nucleosynthesis.

- They form exclusively in a clustered mode.

- They have very short Kelvin-Helmholtz contraction times and hence no optically observable pre-main sequence evolution.

- Large radiation pressure has to be overcome.

- Two main proposals: (1) scale up low-mass star formation scenario (turbulent core model) with accretion disks and enhanced accretion rates. (2) Turn more dynamical, competitive accretion, coalescence and merging.

- Likely a combination of turbulent core and competitive accretion is solution.

- No real evidence for coalescence and merging. Seems not necessary but may exist is selected sources.

- Discussed outflows, disks and clusters.
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